

Precision of Neutron Scattering and Capacitance Type Soil Water Content Gauges from Field Calibration

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ABSTRACT

Soil water content gauges based on neutron scattering (NS) have been a valuable tool for soil water investigations for some 40 yr. However, licensing, training, and safety regulations pertaining to the radioactive source in these devices makes their use expensive and prevents use in some situations such as unattended monitoring. A capacitance probe (CP) gauge has characteristics that would make it seem to be an ideal replacement for NS gauges. We determined the relative precision of two brands of NS gauges (three gauges of each) and a brand of CP gauge (four gauges) in a field calibration exercise. Both brands of NS gauges were calibrated vs. volumetric soil water content with coefficients of determination (r^2) ranging from 0.97 to 0.99 and root mean squared errors (RMSE) $<0.012 \text{ m}^3 \text{ m}^{-3}$ water content. Calibrations for the CP gauges resulted in r^2 ranging from 0.68 to 0.71 and RMSE of $0.036 \text{ m}^3 \text{ m}^{-3}$ water content. Average 95% confidence intervals on predictions were three to five times higher for the CP gauges than for the NS gauges, ranging from 0.153 to $0.161 \text{ m}^3 \text{ m}^{-3}$ and 0.032 to $0.052 \text{ m}^3 \text{ m}^{-3}$, respectively. Although poorly correlated with soil water content, readings were reproducible among the four CP gauges. The poor correlation for CP gauges may be due to small-scale soil water content variations within the measurement volume of the gauge. The NS type gauges provide acceptable precision but that the CP gauge has poor precision and is unacceptable for routine soil water content measurements.

Abbreviations: CP, capacitance probe; CV, coefficient of variation; LC, inductance capacitance; NS, neutron scattering; PVC, polyvinyl chloride; RMSE, root mean square error

Neutron scattering (NS) was first successfully used for measuring soil water content in the 1950's (Gardner and Kirkham, 1952). Since then NS gauges have improved in portability, programmability, weight and size. The advent of more efficient detectors resulted in the use of smaller and thus safer radioactive sources. The precision of measurements possible with NS has

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always been high and satisfactory for many soil water investigations (standard error $<0.01 \text{ m}^3 \text{ m}^{-3}$, Van Bavel et al., 1956; Gardner, 1986). However, safety regulations requiring licensing and training of users, and considerable (and apparently growing) paperwork cause the NS method to remain expensive and difficult or impossible to use in some situations, particularly unattended monitoring. Storage and disposal of gauges is also increasingly expensive. The theory of operation of NS gauges and field calibration methods are described in several publications including Gardner (1986) and Greacen (1981).

A replacement for the NS method would allow measurements in access tubes at any depth and at many field locations. It would be non-nuclear and thus free of regulations pertaining to radioactivity; and capable of stand-alone operation. Better depth resolution and precision at least comparable to the NS method are desirable. A CP gauge with many of these characteristics was described by Dean et al. (1987). The probe consists of an electrode pair separated by a plastic dielectric. The upper and lower electrodes and the plastic separator are in the shape of a cylinder that fits closely inside a plastic access tube. A resonant LC (L = inductance, C = capacitance) circuit in the probe includes the ensemble of the soil outside the access tube, the access tube itself, plus the air space between the probe and access tube, as one of the capacitive elements. Changes in the resonant frequency of the circuit depend on changes in the capacitance of the soil-access tube system. The difference between the resonant frequency of the probe in the access tube and a baseline resonant frequency (often measured with the probe in air) is called the D value and is the value reported by the gauges studied here.

Care is taken to center the capacitance probe in the access tube with minimal space between probe and tube. Access tube installation is also done so as to eliminate air gaps between the tube and soil and minimize soil disturbance. When these conditions are met, changes in the capacitance of the soil-access tube system are those induced by changes in soil water content, temperature, bulk density and macroporosity. The capacitance change caused by water content change is due to the high dielectric constant, K_w (dimensionless), of water which is about 80 and is much higher than that of soil minerals (3 to 5) or air (1).

The capacitance of the soil-access tube system, C (F), is given by (Dean et al., 1987):

$$C = gK_a \quad [1]$$

where K_a is the system apparent dielectric constant and g has units of farads and a value dependant on the geometry of the system. The resonant frequency, F (Hz), is given by (Dean et al., 1987):

$$F = [2\pi(L)^{0.5}]^{-1} (C^{-1} + C_b^{-1} + C_c^{-1})^{0.5} \quad [2]$$

where C_b and C_c are the electrode capacitances including the capacitances of internal circuit elements to which the electrodes are connected, C is the capacitance of the soil-access tube system defined in Eq. [1], and L is the inductance (henries) of the coil in the LC circuit. As soil water content increases, C also increases and F decreases. The temperature dependency is induced by the temperature dependence of water's dielectric constant (assuming that the probe electronics are practically temperature insensitive).

An idea of what the geometry parameter, g , refers to can be obtained from the classical equation for capacitance of a simple two electrode plate capacitor:

$$C = \epsilon_0 K_a a/d \quad [3]$$

where ϵ_0 is the permittivity of free space (8.9×10^{-12} F/m), a is the overlapping area (m^2) of the plates and d is the thickness (m) of the dielectric separating the plates (Malmstadt, et al., 1974, Eq. 2-29). This equation is valid only if the plates are parallel and the dielectric separating the plates is uniform. For this simple capacitor the value of g in Eq. [1] is $\epsilon_0 a/d$.

For the capacitance probe, the soil-access tube system that forms the dielectric between the two probe electrodes is complex, and no relationship has been established for computing g and thus C for this geometry. The plates take the form of two surfaces on a cylinder separated by an insulator, and the access tube and soil are outside of and not between the plates. Thus, the electric field permeating the soil forms a more or less elliptical torus around the probe with lines of force originating in one plate and ending in the other. This was called a *fringing field* by Thomas (1966). Although Eq. [3] does not apply to this configuration, any equation that did apply would have to include terms that describe the plate (electrode) surface area, S , and the interaction of the electric field and the soil volume that it permeates. The latter is described by d in Eq. [3] since the simple geometry of a plate capacitor confines almost all the electromagnetic flux to the volume of dielectric between the plates. For the CP probe electrodes, the surface area of the electrodes is well known but the degree to which the torus of electric force lines permeates the soil is not. Thus, it seems that any term equivalent to d is particularly ill-defined in this soil-access tube system since the soil, with all its variability in bulk density and water content, becomes the dielectric in the capacitive system and the shape of the field may be influenced by soil heterogeneity including any gaps between the soil and tube wall induced by tube installation.

Bell et al. (1987) described methods for access tube installation and calibration for this type of capacitance probe. Plastic tubes were installed with a steel liner and cutting head operating through a guide plate to prevent lateral movement and the creation of air gaps between soil and tube. Installation proceeded in 4-cm increments using a screw auger placed inside the tube and augering no more than 4 cm ahead of the cutting head. All soil was placed in plastic bags and the procedure was assumed to provide a volumetric sample over a 4-cm depth. Calibration of the probe in four soils resulted in coefficients of determination (r^2) ranging from 0.55 to 0.74 for regressions of frequency vs. volumetric water content for three soils, and r^2 of 0.86 and 0.92 for two horizons of the fourth soil. The latter calibration was based on four measurements. Comparison of predicted and measured soil water profiles indicated good correspondance, but the r^2 of some calibrations suggested that standard errors of estimate might be high.

A soil water content CP gauge (Troxler Electronic Laboratories, Inc., model SENTRY 200AP)² was patterned after that of Dean et al. (1987) and included some improvements while retaining the desired characteristics. Heathman (1993) reported an r^2 of 0.62 for a field calibration of this gauge. Our objective was to compare the precision of commercially available NS and CP gauges through field calibration to evaluate the suitability of these gauges for field soil water content measurements.

²The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA-Agricultural Research Service.

MATERIALS AND METHODS

Measurements were made at the USDA-ARS Conservation and Production Systems Research Station at Big Spring, Texas on a field previously planted to cotton (*Gossypium hirsutum* L.). The soil is an Amarillo fine sandy loam (fine-loamy, mixed, thermic Aridic Paleustalf) (F.B. Pringle, USDA-SCS, 1993, personal communication). A sandy clay loam B horizon ($\approx 55\%$ sand, 23% silt, 22% clay) begins at ≈ 30 cm and extends below 200 cm. Within the B horizon a calcic horizon (Btk) starts at about 110 cm and extends below 200 cm. A wet site was created in the dry field by berming a rectangular area approximately 6 m by 4 m and ponding water on the area until the soil profile was wetted to below 2 m. A similar but unbermed area constituting the dry site was about 4 m west of the wet site.

Six neutron scattering gauges were used. Three of these were Campbell Pacific Nuclear², model 503DR gauges (Campbell Pacific Nuclear, Inc., Martinez, CA). The other three were Troxler gauges, of which one was a model 4301 and two were model number 3331. Because the probe diameter for the NS gauges was smaller than that for the CP gauges, the same access tubes could not be used for both. Access tubes for the NS gauges were made of 304-cm lengths of galvanized steel electromechanical tubing (4.4 cm o.d., 4.0 cm i.d.). This is the standard tubing used at the USDA-ARS Conservation and Production Research Lab. and was chosen for its durability and low cost even though aluminum tubing has a lower neutron capture cross section. Plastic tubing was avoided due to its flexibility and higher neutron scattering cross section, which reduces the sensitivity of the probe to soil water content. Three tubes were installed in the wet site and three in the dry site by hand augering a 4.4 cm hole and pushing the tubes in, leaving about 15 cm of tube exposed at the soil surface. The bottom of each tube was beveled inward slightly so that the tube would follow the augered hole as it was pushed in.

Four SENTRY 200 CP gauges were used. Access tubes for the CP gauges were 304-cm lengths of Schedule 40 PVC rigid pipe (6.0 cm o.d., 5.2 cm i.d.). The choice of PVC tubing and its installation followed Troxler guidelines (Troxler Electronic Laboratories, 1991). PVC tubes were beveled on the inside of one end and installed, beveled end down, through a guide plate placed on the soil surface. The guide plate consisted of a 60- by 60-cm square of 1.6-cm-thick plywood in the center of which was rigidly attached a 20-cm long steel pipe machined to just accept the PVC pipe. The guide plate held the PVC tube during installation preventing enlargement of the installation hole near the soil surface. A short hole was augered through the center of the guide plate and the PVC tube was pushed into the soil. Subsequent short sections of the hole were augered from within the PVC tube. The tube was driven into the hole between augerings using a machined driving head (to prevent deformation of the PVC at the top end) and a 4.5-kg hand hammer.

All PVC tubes installed in the dry soil were forced out of round upon entering the calcic horizon at about 110 cm. In two cases installation was stopped when about 120 cm of tube was still above ground. A third tube was installed slightly deeper and a fourth tube was installed fully. In the wet site three PVC tubes were installed in the same manner. All three tubes were fully installed with few problems, but one of the tubes was apparently out of round or bent, so that measurements could not be taken below 163 cm. Tubes were installed or cut off so that the first measurement would be centered at 10 cm below the surface using the built in stops on the capacitance probe extensions. After installation, tubes were cleaned inside with a wire brush.

All soil sampling and gauge readings were done in a 3-d period from 6 to 8 December 1993. The wet site gauge readings and soil sampling were done in one 11-h period to avoid changes in water content due to drainage. To further avoid water content changes due to drainage during sampling, the wet site was allowed to drain for 43 h before sampling began. Sampling with the NS gauges was done at 10 cm and below that at 20-cm increments. Sampling with the CP gauges was done in 15.24-cm increments starting at 10-cm depth. (The 15.24-cm increment was chosen because that is the spacing of the built in stops on the probe handle extensions for the CP gauge.) The 20-cm increment for the NS gauges is the normal sampling increment at the Conservation and Production Research Lab. The sampling depths, which were the same for gauges and soil samples, are given in Table 1.

Table 1. Depths of sampling of Amarillo soil at wet and dry sites (to nearest centimeter). Crosses or dashes indicate samples were taken, spaces indicate no sample, dashes indicate data were not used in regression analyses.

Neutron Scattering							Capacitance							
..... Dry Wet Dry Wet							
Depth	1	2	3	4	5	6	Depth	7	8	9	10	11	12	13
cm							cm							
10	+	+	+	+	+	+	10	+	+	+	+	+	+	+
30	+	+	+	+	+	+	25	+	+	+	+	+	+	—
50	+	+	+	+	+	+	41	+	+	+	+	+	+	—
70	+	+	+	+	+	+	56	+	+	+	+	+	+	—
90	+	+	+	+	+	+	71	+	+	+		+	+	—
110	+	+		+	+		86	+		+		+	+	+
130	+	+		+	+		102	+				+	+	
150	+	+		+	+		117					+	+	
170	+	+		+	+		132					+	+	
190	+	+		+	+		147					+	+	
							163					+	+	

Samples taken by neutron scattering were 1-min counts. Before and after sampling in the access tubes, standard counts were taken with each NS gauge on a stand elevating the gauge bottom 82 cm above the dry soil surface and with the probe locked in the gauge shield. For each gauge the mean standard count was the average of at least six standard counts. For each gauge, the count ratio for each depth in each tube was computed by dividing the sample count taken in the access tube by the mean standard count.

Soil was sampled with the Madera sampler (Allen et al., 1993), which provides a 60-cm³ sample, immediately placed in cans, and the lids sealed with plastic tape. Four samples were taken at each depth. The samples at 10 cm were taken by pushing the sampler vertically into the soil adjacent to the access tube until the sampling volume was centered at 10 cm. For samples below 10 cm a trench was excavated with a backhoe leaving about 10 cm of soil between the trench wall and the tube. To avoid soil compaction or breakage the remaining soil was removed with a spade until one side of the tube was exposed. The tube-soil interface was examined for air gaps and sampling depths were marked on the tube. At each depth four samples were taken horizontally next to the tube using the Madera sampler, with two samples just above and two just below the depth mark. During sampling an air gap was discovered along a length of tube 13 from 25 to 71 cm depth, so samples from depths of 25, 41, 56, and 71 cm at this tube were not considered in data analysis. Although numbered 13 this was actually the first PVC tube installed and overzealous augering ahead of the tube probably caused the air gap. All tubes were inspected for air gaps and no other air gaps were discovered.

Soil cans were tared prior to sampling, weighed after sampling, placed in an oven at 105 C for 48 h, and weighed again. Bulk densities, ρ (Mg m⁻³) and soil water contents, θ (m³ m⁻³) were calculated for each sample and averages computed for each depth.

Calibration equations were explored using linear, stepwise linear, and nonlinear regression; and, confidence limits for predicted values were determined at the 0.05 probability level using the SAS REG and NLIN procedures (SAS Institute, 1987).

For comparison, we also present data from NS gauge calibrations, previously done using the method reported here, on the Ulysses silt loam soil (fine-silty, mixed, mesic Aridic Haplustoll) at Garden City, KS and the Pullman clay loam soil (fine, mixed thermic Torrertic Paleustoll) at Bushland, TX. At Bushland there were only two access tubes each in the wet and dry sites. The coefficients of variation, CV, for θ and ρ were calculated for each depth at each tube.

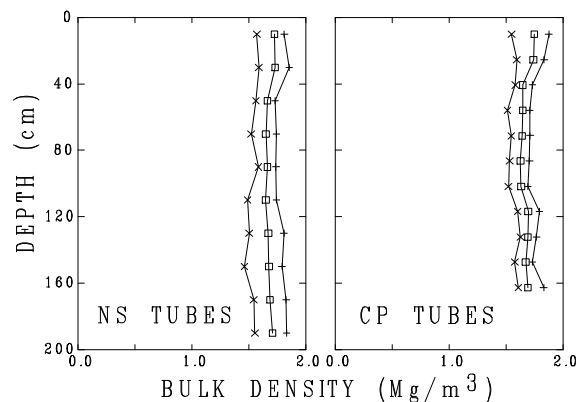


Figure 1. Bulk density profiles for soil at neutron scattering (NS) and capacitance probe (CP) gauge access tubes; mean values (□), minimums (×), and maximums (+).

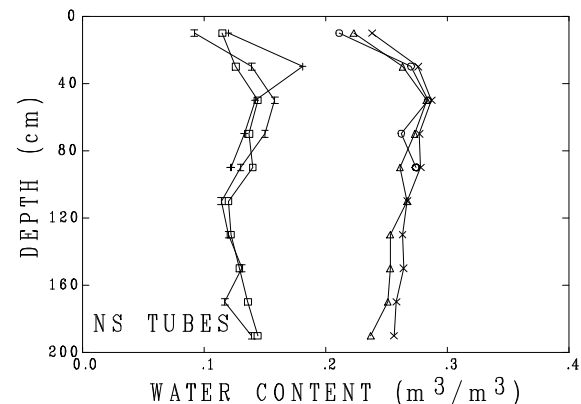


Figure 2. Water content profiles at neutron scattering (NS) access tubes (tubes 1-6); dry site tubes: 1 (□), 2 (×), and 3 (+); and wet site tubes: 4 (×), 5 (Δ), and 6 (○).

RESULTS AND DISCUSSION

There was little variability of ρ with depth at Big Spring. Mean values were close to 1.7 Mg m^{-3} throughout the profile (Fig. 1). There was little difference in average ρ measured at the six NS access tubes compared with that measured at the seven CP gauge access tubes, but there was slightly less variability in individual sample ρ measured at the CP gauge access tubes. The θ profiles illustrate the wide range of water contents achieved at the wet and dry sites (Fig. 2 and 3).

For the NS gauges, separate linear regressions of θ vs. count ratio were performed for the A horizon, the complete B horizon, the B horizon above the calcic interface, and the calcic B horizon. Regressions resulted in r^2 of 0.97 and above, $\text{RMSE} < 0.012 \text{ m}^3 \text{ m}^{-3}$, and small 95% confidence intervals on the predictions (Table 2, Fig. 4). The average 95% confidence interval on predictions ranged from 0.032 to $0.052 \text{ m}^3 \text{ m}^{-3}$ for the six NS gauges in the B horizon above the calcic B (30- to 90-cm depth range).

For the CP gauges, regressions were calculated for the A horizon (readings at 10 cm depth) and the B horizon above the calcic interface (41- to 102-cm depth range). Samples taken at 25 cm were not included in either the A or B horizon calculations because of the heterogeneity at this depth near the B horizon interface. The calcic B horizon was ignored because too few samples were taken in it at the dry site. Three regression models were tried. The first, based on the model used for factory calibration (Troxler Electronic Laboratories, 1991), was:

$$D = B_0 \exp(100B_1\theta) + B_2 \quad [4]$$

where D is the absolute value of the frequency shift measured by the gauge and B_0 , B_1 , and B_2 are regression parameters. This model was fit to the data using the SAS NLIN procedure for nonlinear regression (SAS Institute, 1987). The second model used was quadratic in θ ($D = B_0 + B_1\theta + B_2\theta^2$) and the third was a linear equation.

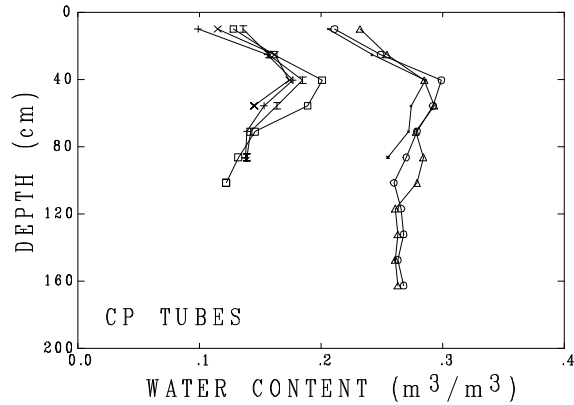


Figure 3. Water content profiles at capacitance probe (CP) gauge access tubes (tubes 7-13); dry site tubes: 7 (\square), 8 (\circ), 9 (+), and 10 (\times); and wet site tubes: 11 (Δ), 12 (\circ), and 13 (\bullet).

Table 2. Regression equations for neutron scattering water content gauges.

Serial no. [†]	Model	Regression equation	r ²	RMSE [‡]	n
				m ³ m ⁻³	
A horizon (10-cm depth)					
5447	503DR	$\theta = 0.014 + 0.2172(\text{CR})^{\S}$	0.997	0.004	6
6190	503DR	$\theta = 0.001 + 0.2196(\text{CR})$	0.999	0.002	6
0698	503DR	$\theta = 0.021 + 0.2105(\text{CR})$	0.996	0.005	6
386	3331	$\theta = 0.054 + 0.5270(\text{CR})$	0.992	0.006	6
385	3331	$\theta = 0.028 + 0.5388(\text{CR})$	0.997	0.004	6
326	4301	$\theta = 0.001 + 0.4943(\text{CR})$	0.999	0.002	6
B horizon above calcic B (30- to 90-cm depth)					
5447	503DR	$\theta = -0.066 + 0.2421(\text{CR})$	0.988	0.008	24
6190	503DR	$\theta = -0.070 + 0.2464(\text{CR})$	0.982	0.009	24
0698	503DR	$\theta = -0.070 + 0.2273(\text{CR})$	0.989	0.007	24
386	3331	$\theta = -0.003 + 0.5206(\text{CR})$	0.985	0.009	24
385	3331	$\theta = -0.016 + 0.5406(\text{CR})$	0.985	0.009	24
326	4301	$\theta = -0.010 + 0.4646(\text{CR})$	0.970	0.012	24
Calcic B horizon (110- to 190-cm depth)					
5447	503DR	$\theta = -0.057 + 0.2299(\text{CR})$	0.992	0.006	20
6190	503DR	$\theta = -0.062 + 0.2352(\text{CR})$	0.992	0.006	20
0698	503DR	$\theta = -0.053 + 0.2086(\text{CR})$	0.992	0.006	20
386	3331	$\theta = 0.001 + 0.5049(\text{CR})$	0.993	0.006	20
385	3331	$\theta = -0.014 + 0.5276(\text{CR})$	0.993	0.006	20
326	4301	$\theta = -0.017 + 0.4741(\text{CR})$	0.992	0.006	20
Complete B horizon (30- to 190-cm depth)					
5447	503DR	$\theta = -0.063 + 0.2371(\text{CR})$	0.988	0.007	44
6190	503DR	$\theta = -0.067 + 0.2419(\text{CR})$	0.984	0.008	44
0698	503DR	$\theta = -0.062 + 0.2189(\text{CR})$	0.987	0.008	44
386	3331	$\theta = -0.001 + 0.5142(\text{CR})$	0.988	0.007	44
385	3331	$\theta = -0.016 + 0.5360(\text{CR})$	0.988	0.008	44
326	4301	$\theta = -0.013 + 0.4696(\text{CR})$	0.979	0.010	44

[†]Three-digit numbers refer to Troxler Electronic Laboratories gauges; four-digit numbers refer to Campbell Pacific Nuclear gauges.

[‡]RMSE is root mean squared error.

[§]CR is the count ratio, which is then neutron count in the access tube divided by the standard count.

For both the A and B horizons, parameters B_0 and B_1 were not significantly different from zero (5% level) for the exponential model applied to data from any of the four CP gauges, but the intercept parameter B_2 was significant in all cases. Parameters B_1 and B_2 in the quadratic model were not significantly different from zero for both horizons. For the B horizon, the intercepts (B_0) were significant in all cases for the quadratic model. For the A horizon, the intercepts for the quadratic model were significant in 3 cases. In the fourth case (gauge ser. no. 255) the intercept would have been significant at the 0.07 level. The significance of the intercept terms in the exponential and quadratic models, for which θ is the independent variable, is not surprising since the intercepts are far from zero (≈ 4000 - 4500 for the four gauges) while the standard deviations of D are relatively small compared to the intercept values. The exponential and quadratic models were omitted from further consideration due to the insignificant parameters. It may be that the wide separation of water contents between the wet and dry sites makes a non-linear fit to these data more difficult (see Fig. 4 and 5).

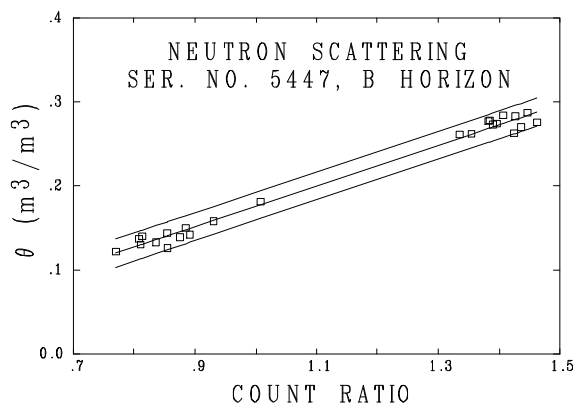


Figure 4. Typical volumetric water content (θ) vs. count ratio relationship in the B horizon (tubes 1-6). Middle line is the regression line, upper and lower lines are 95% confidence limits on predictions.

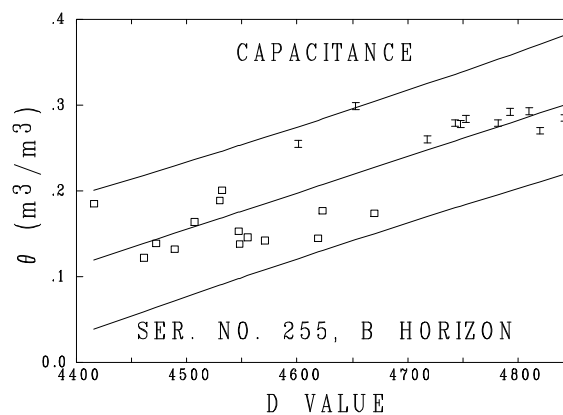


Figure 5. Typical relationship between volumetric water content (θ) and the absolute value of the measured frequency shift (D) from capacitance gauges (tubes 7-13), showing dry site data (\square) and wet site data (\circ). Solid line is the regression line, upper and lower lines are 95% confidence limits on predictions.

For convenience, the linear model was applied with D as the independent variable ($\theta = B_0 + B_1 D$). Both parameters (intercept and slope) in the linear model were insignificant for the A horizon data for all CP gauges but are reported for information (Table 3). (Note that if the model is stated as $D = B_0 + B_1 \theta$ then the intercepts, but not the slopes, are significant).

For the B horizon, both parameters in the linear model were significant for all CP gauges with r^2 ranging from 0.68 to 0.71 (Table 3). Root mean squared errors ranged from 0.036 to 0.037 $\text{m}^3 \text{m}^{-3}$. The average 95% confidence interval on predictions ranged from 0.153 to 0.161 $\text{m}^3 \text{m}^{-3}$ for the four CP gauges, about four times greater than for the NS gauges. A typical plot shows the scatter of data around the linear regression line (Fig. 5). Despite the poor relationship between water content and D value the readings of each of the four CP gauges were consistent when compared against the mean of the four instruments (Fig. 6, Table 3). The low RMSE (16-27 D units in Table 3) indicates that

the precision of the gauges was good. This, coupled with the poor calibration results, suggests that something other than the average water content of the measurement volume was being measured very well. The measured factor was highly variable around the access tubes.

Table 3. Regression equations for the capacitance type water content gauges; water content vs. D value, and D value vs. mean D value.

Serial no.	Regression equation	r^2	RMSE [†] m ³ m ⁻³	n
A horizon (10-cm depth)				
255	$\theta = -0.140 + 0.000073(D)$	0.041	0.058	7
256	$\theta = -0.700 + 0.000215(D)$	0.211	0.052	7
257	$\theta = -0.273 + 0.000115(D)$	0.019	0.058	7
294	$\theta = -0.110 + 0.000067(D)$	0.010	0.058	7
B horizon (41- to 102-cm depth)				
255	$\theta = -1.750 + 0.000423(D)$	0.698	0.036	25
256	$\theta = -1.460 + 0.000365(D)$	0.712	0.036	25
257	$\theta = -1.404 + 0.000380(D)$	0.681	0.037	25
294	$\theta = -1.583 + 0.000410(D)$	0.704	0.036	25
D value vs. Mean D value (41- to 102-cm depth)				
255	$D = 500 + 0.93(\text{Mean } D)$	0.970	23	25
256	$D = -271 + 1.09(\text{Mean } D)$	0.974	25	25
257	$D = -339 + 1.03(\text{Mean } D)$	0.989	16	25
294	$D = 110 + 0.96(\text{Mean } D)$	0.960	27	25

[†]RMSE is root mean squared error.

There is evidence that soil dielectric constant (and thus capacitance) is sensitive to soil texture (Wobschall, 1978; Kuráž, 1981; Hallikainen et al., 1985; Bell et al., 1987). Because clay content varied with depth in our soil, we performed separate linear regression analyses for each CP gauge for each sampling depth in the B horizon and at the 25-cm depth (Table 4). At 25- and 41-cm depths coefficients of determination were below 0.5. For the 25-cm depth this can be explained by noting that the B horizon begins at this depth and texture and bulk density vary greatly over a short vertical distance. At the 41-cm depth the probe is well within the B horizon and at the depth at which clay content is greatest. For 56-, 71-, 86-, and 102-cm depths results were rather better but not consistently so with RMSE ranging from 0.002 to 0.045 m³ m⁻³. The low number of samples in these

regressions leaves considerable room for error. In particular the high r^2 values for the 102-cm depth are for regressions involving only three samples and so could easily be the result of chance. With such low sample numbers we would not want to claim that the higher r^2 values at greater depths are evidence that the CP gauge should be calibrated layer by layer.

Some possible sources of variability in the CP gauge readings can be discounted. For instance, Dean et al. (1987) showed that, for their design, total thermal (0-30°C) and temporal (over 3 h) stability errors amounted to $<0.005 \text{ m}^3 \text{ m}^{-3}$ error in water content. They also showed that air gaps between the tube and soil would introduce large errors, thus the exacting tube installation procedure. They did not measure the probe's sensitivity to ρ variations but in a companion paper Bell et al. (1987) noted that ρ appeared to affect the slope of calibration equations and concluded that more work was required in this area.

Because we had some difficulty installing PVC tubes in the dry site one might conjecture that the D values from dry site tubes were more variable due to possible soil disturbance. However, consideration of Fig. 5 and similar plots for the other CP gauges does not show a better relationship between θ and D for samples from the wet site, where tubes were installed easily, compared with the θ vs. D relationship for samples from the dry site. In fact, for either site considered alone the relationship between θ and D is essentially flat with little change in θ for a relatively wide spread of D values.

In preliminary data analysis we used stepwise linear regression of θ against D value, D^2 , ρ , ρ^2 , and $\rho^{0.5}$ to find the independent variable(s) that were a significant source of variability in the dependent variable. Other than the intercept, only the coefficient for D^2 was significant at the 0.50 level of probability. For the model, $\theta = B_0 + B_1 D^2$, the coefficient for D^2 was so low ($B_1 = 4.6 \times 10^{-8}$) that the plot of θ vs. D was nearly linear and differed only slightly from a plot of the linear model. Because of this and the low significance of the $\theta = B_0 + B_1 D^2$ relationship, this model was omitted from further consideration.

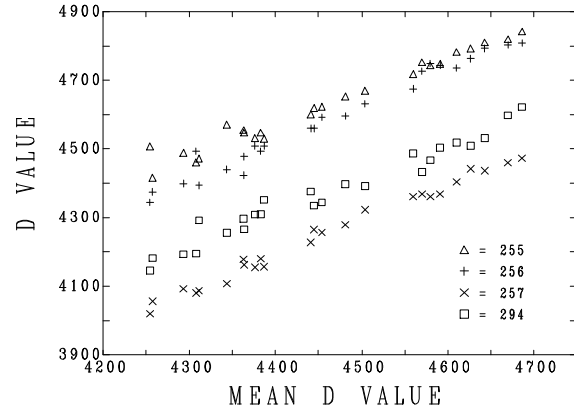


Figure 6. Consistency of capacitance gauge readings shown by plotting the absolute value of the measured frequency shift (D) vs. mean D value of four gauges for each sample (B horizon). Legend shows gauge serial numbers.

Table 4. Regression equations for the capacitance probe soil water content gauges by depth in the B horizon above the calcic B: water content (θ) vs. the frequency difference from the capacitance gauge (D).

Serial no.	Regression equation	r^2	RMSE [†] m ³ m ⁻³	n
25-cm depth				
255	$\theta = -0.996 + 0.000264(D)$	0.185	0.048	6
256	$\theta = -0.711 + 0.000203(D)$	0.144	0.050	6
257	$\theta = -0.527 + 0.000174(D)$	0.117	0.050	6
294	$\theta = -0.759 + 0.000221(D)$	0.415	0.041	6
41-cm depth				
255	$\theta = -0.835 + 0.000228(D)$	0.333	0.052	6
256	$\theta = -0.753 + 0.000212(D)$	0.288	0.053	6
257	$\theta = -0.680 + 0.000211(D)$	0.285	0.054	6
294	$\theta = -0.882 + 0.000252(D)$	0.413	0.048	6
56-cm depth				
255	$\theta = -1.908 + 0.000456(D)$	0.808	0.034	6
256	$\theta = -1.378 + 0.000346(D)$	0.753	0.038	6
257	$\theta = -1.226 + 0.000337(D)$	0.671	0.044	6
294	$\theta = -1.568 + 0.000406(D)$	0.710	0.041	6
71-cm depth				
255	$\theta = -2.507 + 0.000585(D)$	0.920	0.024	5
256	$\theta = -1.686 + 0.000414(D)$	0.994	0.007	5
257	$\theta = -2.063 + 0.000536(D)$	0.953	0.019	5
294	$\theta = -2.628 + 0.000647(D)$	0.966	0.016	5
86-cm depth				
255	$\theta = -1.918 + 0.000158(D)$	0.740	0.044	5
256	$\theta = -1.578 + 0.000391(D)$	0.781	0.040	5
257	$\theta = -1.609 + 0.000428(D)$	0.745	0.044	5
294	$\theta = -1.564 + 0.000407(D)$	0.730	0.045	5
102-cm depth				
255	$\theta = -2.110 + 0.000501(D)$	0.994	0.010	3
256	$\theta = -2.894 + 0.000672(D)$	0.982	0.016	3
257	$\theta = -1.863 + 0.000487(D)$	0.999	0.002	3
294	$\theta = -1.883 + 0.000478(D)$	0.999	0.002	3

[†]RMSE is root mean squared error.

The CP gauge is responsive mostly to a soil layer as thin as 8 cm (Bell et al., 1987) or 12 cm (Troxler Electronic Laboratories, 1993) vertically, and within 11 cm of the probe centerline (Troxler Electronic Laboratories, 1993). Thus, small-scale variations in soil properties are more likely to influence the probe's readings than would be the case for the NS gauge. Our soil samples were generally taken within the 11-cm radius and 12-cm vertical range but there was considerable variation in individual water contents for a given depth and access tube. The electric field induced in the soil by the CP is influenced by boundaries between soil volumes having different dielectric constants (Dean et al., 1987). Thus, ρ or θ variations on a small scale could set up boundaries that would influence the size and shape of the sampled volume. Boot and Watson (1964) noted that sample heterogeneities can cause anomalous readings from capacitance probes applied to building materials, especially when the wavelength approaches the scale of heterogeneity. Wobschall (1978) pointed out that heterogeneous soils can also cause poor results.

Because we had multiple θ and ρ measurements at each depth and for each access tube, we were able to compare the mean CVs of these parameters at each depth from the NS calibrations done at Bushland, TX and Garden City, KS with the results from this study (Fig. 7 and 8). There was little difference in the mean CV for ρ at each depth in the Amarillo soil compared with results for the Ulysses and Pullman soils (Fig. 7). Also, for the 41- to 102-cm depth range the mean CV for θ at each depth for the Amarillo soil was comparable to that for the Ulysses and Pullman soils (Fig. 8). Within this depth range the mean CV for θ ranged from 0.030 to 0.035 for NS tubes and from 0.025 to 0.056 for CP tubes in Amarillo soil, from 0.010 to 0.021 in Ulysses soil, and from 0.025 to 0.038 in Pullman soil. These soils are representative of the major soils in the Southern High Plains so it appears that the Amarillo soil is not more heterogeneous in the B horizon than other soils in this area. The large mean CV for θ at 25-cm depth for the Amarillo soil is due to the abrupt textural change at this depth and is probably related to the low r^2 values for this depth for the CP gauge regression equations in Table 4. This is evidence for what we speculate is the tendency of the CP gauge to

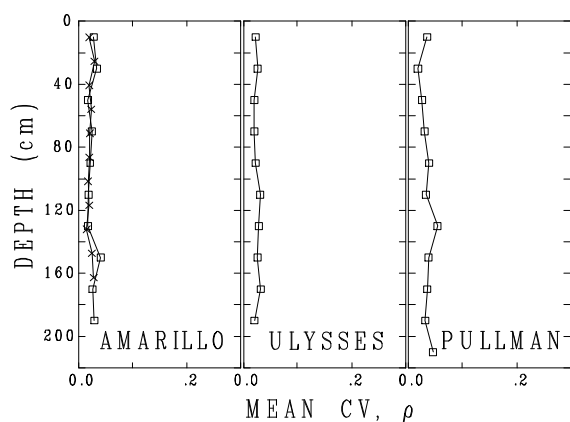


Figure 7. Mean coefficient of variation, CV, for bulk density, ρ , at each depth for the Amarillo (neutron scattering access tubes = \square , capacitance probe access tubes = \times), Ulysses, and Pullman soils.

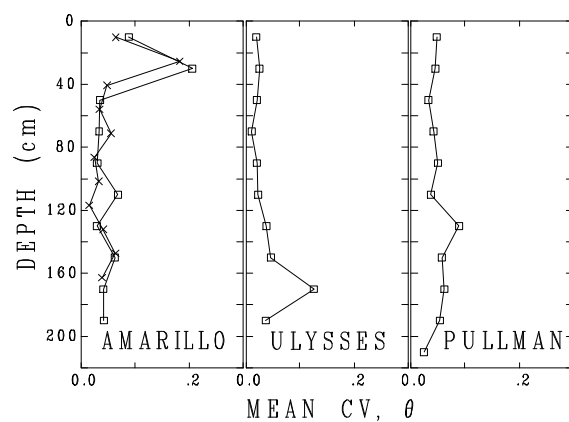


Figure 8. Mean coefficient of variation, CV, for water content, θ , at each depth for the Amarillo (neutron scattering access tubes = \square , capacitance probe access tubes = \times), Ulysses, and Pullman soils.

respond non-uniformly to variations of water content within its volume of measurement; or, put another way, the tendency of the measurement volume of this gauge to change in shape and size in response to variations in water content. However, the r^2 values for the CP gauge regressions for the other depths (41, 56, 71, and 86 cm) in Table 4 do not appear to follow the trends in average CV of θ at these depths shown in Figure 8.

Another possible explanation for the poor results with the CP gauges is that the measurement volume is considerably smaller than reported by Bell et al. (1987) and Troxler Electronic Laboratories (1993). If this were so then the soil sampling method that we used would be inappropriate. However, the 15.24-cm measurement interval provided by the stops on the CP gauge probe handle would be too large if the sampling volume were smaller than that stated by Troxler Electronic Laboratories (1993). If the sampling volume is indeed much smaller than reported, then the use of the CP gauge must be reevaluated because many more samples at much smaller vertical sampling intervals must be taken to provide accurate integration of the soil water content profile. In fact, if this hypothesis is true it may be difficult to accurately portray the soil water content profile in many soils because the representative elemental volume may be larger than the gauge's sampling volume. Field calibration of this gauge would also be problematic in this case because an exacting relationship between probe position in the tube and position of soil sampling is implied.

We conclude that the CP gauge has limited precision and is unacceptable for soil water content measurements under our conditions. In a less heterogeneous soil this might not be true. However, we have presented evidence that our soil was not more heterogeneous than most. In the literature there is evidence suggesting that small scale heterogeneities in ρ and θ may affect the reliability of CP gauge readings. This effect may be one of distorted or biased sample volume since the shape of the electric field may be changed. We have presented some evidence that this happened in our study. If it is true that soil heterogeneities affect the shape of the CP gauge sample volume or bias the sample in other ways, then the capacitance method may be sufficiently compromised to curtail its use. This is a serious question that warrants further research.

The good results with the NS devices, while unsurprising, further illustrate the usefulness of this technique as does the similarity of results from both brands of NS gauges that we used. Regulatory pressures notwithstanding, these results should encourage the continued use of NS gauges.

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REFERENCES

- Allen, R.G., G. Dickey, J.L. Wright, J.F. Stone, and D.J. Hunsaker. 1993. Error analysis of bulk density measurements for neutron moisture gauge calibration. p. 1120-1127 *In* Management of irrigation and drainage systems, integrated perspectives. Proc. 1993 ASCE Natl. Conf. Irrig. Drain. Eng., Park City, UT, 21-23 July 1993. Am. Soc. Civ. Eng., New York.
- Bell, J.P., T.J. Dean, and M.G. Hodnett. 1987. Soil moisture measurement by an improved capacitance technique: Part II. Field techniques, evaluation and calibration. *J. Hydrol. (Amsterdam)* 93:79-90.
- Boot, A.R., and A. Watson. 1964. Applications of centrimetric radio waves in nondestructive testing. p. 3-24 *In* ASTM-RILEM Symp. Appl. Adv. Nucl. Phys. Testing Materials. Texas A&M University, College Station.
- Dean, T.J., J.P. Bell, and A.J.B. Baty. 1987. Soil moisture measurement by an improved capacitance technique: Part I. Sensor design and performance. *J. Hydrol. (Amsterdam)* 93:67-78.
- Gardner, W., and D. Kirkham. 1952. Determination of soil moisture by neutron scattering. *Soil Sci.* 73:391-401.
- Gardner, W.H. 1986. Water content. p. 493-544 *In* A. Klute (ed.) *Methods of soil analysis*, Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.
- Greacen, E.L. 1981. Soil water assessment by the neutron method. CSIRO, Melbourne, Australia.
- Hallikainen, M.T., F.T. Ulaby, M.C. Dobson, M.A. El-Rayes, and L. Wu. 1985. Microwave dielectric behavior of wet soil. Part I: Empirical models and experimental observations. *IEEE Trans. Geosci. Remote Sens.* GE-23(1):25-34.
- Heathman, G.C. 1993. Soil moisture determination using a resonant frequency capacitance probe. Paper no. 931053. ASAE, St. Joseph, MI.
- Kuráž, V. 1981. Testing of a field dielectric soil moisture meter. *ASTM Geotechn. Test. J.* 4:111-116.
- Malmstadt, H.V., C.G. Enke, S.R. Crouch, and G. Horlick. 1974. Electronic measurements for scientists. W.A. Benjamin, Menlo Park, CA.
- SAS Institute. 1987. SAS/STAT guide for personal computers, version 6 ed. SAS Inst., Cary, NC.
- Thomas, A.M. 1966. *In situ* measurement of moisture in soil and similar substances by 'fringe' capacitance. *J. Sci. Instrum.* 43:21-27.
- Troxler Electronic Laboratories. 1991. Manual of operation and instruction, Sentry 200-AP. Troxler Electronic Lab. Research Triangle Park, NC.
- Troxler Electronic Laboratories. 1993. Troxler technical brief: Comparing the Sentry 200-AP and the model 4300 moisture probes. Troxler Electronic Lab., Research Triangle Park, NC.
- Van Bavel, C.H.M., N. Underwood, and R.W. Swanson. 1956. Soil moisture measurement by neutron moderation. *Soil Sci.* 82:29-41.
- Wobschall, D. 1978. A frequency shift dielectric soil moisture sensor. *IEEE Trans. Geosci. Electron.* GE-16(2):112-118.